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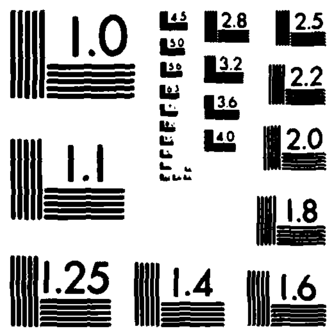

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FOREIGN TECHNOLOGY DIVISION

MEASURING THE DIELECTRIC CONSTANT AND SPECIFIC CONDUCTIVITY OF SOIL

by

I.Ye. Balygin and V.I. Vorob'yev

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Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	$\sinh^{-1}$
cos	cos	ch	cosh	arc ch	$\cosh^{-1}$
tg	tan	th	tanh	arc th	$\tanh^{-1}$
ctg	cot	cth	coth	arc cth	$\coth^{-1}$
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

MEASURING THE DIELECTRIC CONSTANT AND SPECIFIC CONDUCTIVITY OF SOIL

I. Ye. Balygin and V. I. Vorob'yev

Values of ε and σ are measured in soil (coarse-grain sand) under different weather conditions.

Knowledge of electrical properties of soil is very important for both radio engineers and people working in the field of high-current technology. In the case of all electromagnetic-wave propagation processes, the specific conductivity of soil σ and its dielectric constant ε, which characterize the electrical properties of the soil, are, as we know taken into account in the expression for the coefficient of refraction, the square of which is equal to:

$$n^2 = \varepsilon - 6\cdot 10^{3}\sigma\lambda\sqrt{-1},$$

where λ represents the wavelength in meters, ε - in electrostatic and σ - in practical units (siemens/cm). On n^2 depend both total resistance to antenna radiation and antenna radiation absorbed by the Earth [1].

Existing formulas employed in the design of electrical groundings always incorporate the specific conductivity of the soil (σ) at the point of the ground: to design these grounds accordingly requires that we know this value. The computations given by Fortescue [2] for long grounds, apparently called upon to play a major role in protecting transmission lines from direct lightning strokes in (rocky) areas of

very high specific soil resistance, also that require that we know ε. For the wave resistance of this kind of ground (counterpoises), Aigner [3], for example, gives the formula

$$|Z| = \frac{1}{2\pi}\sqrt[4]{\frac{\mu^2\mu_0^2}{\varepsilon^2\varepsilon_0^2 + \sigma^2T^2}}\ln\frac{R}{r},$$

where R represents the depth of the counterpoise, r the radius of the counterpoise, $T = 1/\omega$ the pulse wave time constant, 0 to max (equivalent angular frequency), while ε_0 and μ_0 are constants. Computations using this formula accordingly require that we know values of ε and σ for the soil at the point of the ground.

Taking into consideration the extreme heterogeneity of the soil even over very short distances both horizontally and vertically, from the point of view of practical value, all measurements with portions of soil taken for experimental purposes from one place or another on a test area must be seen to be unsuitable. What we have to do is measure average ε and σ for soil over a fairly considerable distance, which is especially important for computations involving extended grounds. Since ground cover on the soil is evidently a factor in determining electrical properties of the latter, we must conclude that measurements made where future grounds are to be located would be of greatest value. If we look at everything said so far about the importance of knowing ε and σ from the point of view of applying this information to the process of designing grounds to protect communication lines against atmospheric overvoltages, we must also bear in mind the importance of accumulating experimental data for a study of the electrical properties of soil in the various areas these lines cross or in which it is proposed to construct them. From this point of view there can be no doubt of the interest attaching to measurements of the electrical properties of soil in different geographical regions of the Union. Among such measurements made abroad, we would point to German tests conducted in the Telefunken laboratory by Abraham, jointly with Rausch von Traubenberg and Pusch [4]. of a method of attenuating high-frequency electromagnetic waves in a Lecher system buried in the ground to a depth of 30 cm. Abraham [5] has elaborated the theory involved, which is presented in general outline below.

These were experiments to measure only σ (on comparatively long waves with λ ranging from 280 to 1170 m) in meadow soil. It was found that σ is not a function of λ when the latter ranges between 280 and 880 m. In a case of very moist soil, with λ varying between 660 and 1130 m, σ ranged accordingly between $8.6 \cdot 10^{-5}$ and $6.5 \cdot 10^{-5}$ siemens/cm. When λ varied between 610 and 1170 m in moist soil, σ varied between $8.1 \cdot 10^{-5}$ and $7.8 \cdot 10^{-5}$. Employing what is theoretically the same method, Strutt [6] (Germany), working with shorter waves (from 3000 to 100 m), computed both ε and σ also for meadow soil. According to his measurements, ε = 10, 15 in the same soil after rain. In this range ε depends only slightly upon frequency. These values were measured in England by Ratcliffe and Show [7] in the Cavendish laboratory at Cambridge. The theory of electromagnetic wave attenuation given by Sommerfeld [8] constituted the basis for these measurements. According to this theory, we can construct a curve of wave attenuation as a function of distance from a source located on the surface of a conducting dielectric. Measuring the attenuation of 30-m waves on various segments to 11,400 m and comparing the experimental curve with the theoretical curve, Ratcliffe and Show calculated ε and σ, which proved equal to 20 electrostatic units and $2 \cdot 10^{-5}$ siemens/cm respectively.

To measure ε and σ, we used the method referred to above, first mentioned by Abraham. Given certain assumptions, the theory underlying this method derives from solution of the known Maxwell equations for parallel conductors in an unbounded medium with dielectric constant ε, specific conductivity σ and permeance μ. Assuming that coordinate axis X is parallel to the conductors, and disregarding the resistance of the latter, while, accordingly, assuming components E_x and H_x equal to 0, we obtain

$$\left.\begin{aligned} \frac{\varepsilon}{C}\frac{\partial E_y}{\partial t}+\frac{4\pi\sigma}{C}E_y &= -\frac{\partial H_z}{\partial x} \\ \frac{\varepsilon}{C}\frac{\partial E_z}{\partial t}+\frac{4\pi\sigma}{C}E_z &= \frac{\partial H_y}{\partial x} \end{aligned}\right\} \quad (1)$$

$$\left.\begin{aligned} -\frac{\mu}{C}\frac{\partial H_y}{\partial t} &= \frac{\partial E_z}{\partial x} \\ -\frac{\mu}{C}\frac{\partial H_z}{\partial t} &= \frac{\partial E_y}{\partial x} \end{aligned}\right\} \quad (2)$$

As is known, from these two systems of equations we can easily derive two new equations for E_y and E_z, from which directly derive the telegraph equation:

$$\frac{1}{\mu\mu_0}\frac{\partial^2 E}{\partial x^2} = \sigma\frac{\partial E}{\partial t} + \varepsilon\varepsilon_0\frac{\partial^2 E}{\partial t^2}. \qquad (3)$$

where

$$\varepsilon_0 = \frac{1}{4\pi\cdot 9\cdot 10^{11}}\,\frac{F}{cm}, \quad \mu_0 = 4\pi\cdot 10^{-9}\,\frac{H}{cm};$$

ε is in electrostatic, σ in electrical units.

We will have an analogous expression for voltage V, since the equality $V = \int_0^b E_y\,dy$ depends neither upon x nor on t.

Solving this equation by the substitution

$$V = V_0 e^{-j\omega t} e^{jkx}, \qquad (4)$$

where $\omega = \frac{2\pi C}{\lambda}$ represents the frequency of nonattenuating oscillations in air, we obtain for K the expression

$$K = \sqrt{\mu\mu_0\varepsilon\varepsilon_0\omega^2 + j\omega\mu\mu_0\sigma} = \alpha + j\beta, \qquad (5)$$

whence

$$\alpha = \sqrt{\frac{\mu\mu_0\omega\left[\varepsilon\varepsilon_0\omega + \sqrt{(\varepsilon\varepsilon_0\omega)^2 + \sigma^2}\right]}{2}}, \qquad (6)$$

$$\beta = \sqrt{\frac{\mu\mu_0\omega\left[-\varepsilon\varepsilon_0\omega + \sqrt{(\varepsilon\varepsilon_0\omega)^2 + \sigma^2}\right]}{2}}, \qquad (7)$$

hence

$$V = V_0 e^{-\beta x} e^{j(\alpha x - \omega t)}. \qquad (8)$$

We can see from the last equation that β expresses the spatial attenuation of electromagnetic waves propagated along the wires of

the Lecher system, while (ω/α) represents the speed with which these waves propagate in the conducting medium. Formula (8), of course, is applicable to a Lecher system only if there are no reflections from the open end of this system. It is accordingly assumed that waves are completely attenuated before they reach the end of the wires.

If we now measure the voltage at different distances X from the source of nonattenuating oscillations, we can find β, which is computed in accordance with (8) from:

$$\beta = -\frac{1}{x} \ln \left| \frac{V}{V_0} \right|. \tag{9}$$

Knowing β is not enough to compute ε and σ, since we have one equations with two unknowns. What we can do, of course, is do what Strutt [6] did and employ the curve of attenuation β as a function of wavelength and, disregarding displacement currents in the case of long waves, use this curve to compute first σ and then ε. But, employing these constructions of Abraham, we can also derive another equation, which, with additional measurements, supplies the missing data required for full determination of ε and σ.

For the specific cross section of the parallel wires, the following relationship occurs between induction flux and current:

$$\Phi = LI \cdot 10^{8}. \tag{10}$$

where L represents self-induction in henrys per unit length of the parallel wires, which is computed in accordance with the following formula:

$$L = 4 \cdot 10^{-9} \mu \ln \frac{h}{\rho} \tag{11}$$

when $\rho \ll h$. Here h represents the distance between wires and ρ their radius.

From the relationship between induction flux Φ and voltage V (equation 2), we can derive the equation [9]:

$$\frac{\partial \Phi}{\partial t} = -10^{8}\frac{\partial V}{\partial x}. \qquad (12)$$

Taking equation (10) into account, we obtain:

$$\frac{\partial V}{\partial x} = -L\frac{\partial I}{\partial t}. \qquad (13)$$

The telegraph equation for current from systems of equations (1 and 2) is analogous to equation (3), for which the solution will also be precisely:

$$I = I_0 e^{-i\omega t} e^{ikx}. \qquad (14)$$

Taking equations (4), (13) and (14), we obtain:

$$V_0 = \frac{\omega L}{K} I_0. \qquad (15)$$

If we substitute in place of K its value from (5), we will have:

$$V_0 = \frac{\omega L(\alpha - i\beta)}{\alpha^2 + \beta^2} I_0. \qquad (16)$$

Here $V_0 e^{-i\omega t}$ and $I_0 e^{-i\omega t}$ represent voltage and current at the source of oscillation. From (16) we obtain:

$$R_0 = \frac{\omega L \alpha}{\alpha^2 + \beta^2}. \qquad (17)$$

$$L_0 = \frac{L\beta}{\alpha^2 + \beta^2}. \qquad (18)$$

R_0 and L_0 will represent the equivalent resistance and equivalent self-induction respectively of the Lecher system (Fig. 1).

Thus, if we measure current and voltage at the source of non-attenuating oscillations, we will obtain the missing equation for computing ε and σ, namely:

$$Z_0 = \frac{L\omega}{\sqrt{\alpha^2 + \beta^2}}. \tag{19}$$

From (6), (7) and (19) we finally obtain:

$$\varepsilon = \frac{\omega^2 L^2 - 2\beta^2 Z_0^2}{2Z_0^2 \mu \mu_0 \varepsilon_0 \omega^4}, \tag{20}$$

$$\sigma = \sqrt{\left(\frac{2\alpha\beta}{\mu\omega}\right)^2 + \frac{4\beta^2 \varepsilon_0}{\mu_0}}. \tag{21}$$

In view of the absence in the measuring system of substances which can be magnitized, μ may be assumed to be equal to one.

Values of ε and σ were measured in a forest clearing in the vicinity of a 500 kV LEFI [Leningrad Institute of Electrophysics] experimental communication line in coarse-grain sandy soil. The Lecher system consisted of two parallel wires 140 m in length positioned 2 cm from one another and buried in the ground to a depth of 50 cm. This great wire length was necessary so that the waves would be able to attenuate before they reached the end of the wires.

Fig. 1.

Fig. 2.

Fig. 1. Circuit of equivalent Lecher system.

Fig. 2. Scheme for measuring soil ε and σ.

At distances of l = 2.5, 5, 10, 20 and 50 m we brought leads to the surface to permit measurement of the attenuation of electromagnetic wave amplitude.

The theory set forth above, of course, is strictly applicable only to wires in an infinitely long conducting medium; but since the energy processes involved occur in the immediate vicinity of the wires, limiting the depth to 50 cm only slightly distorts measurement results.

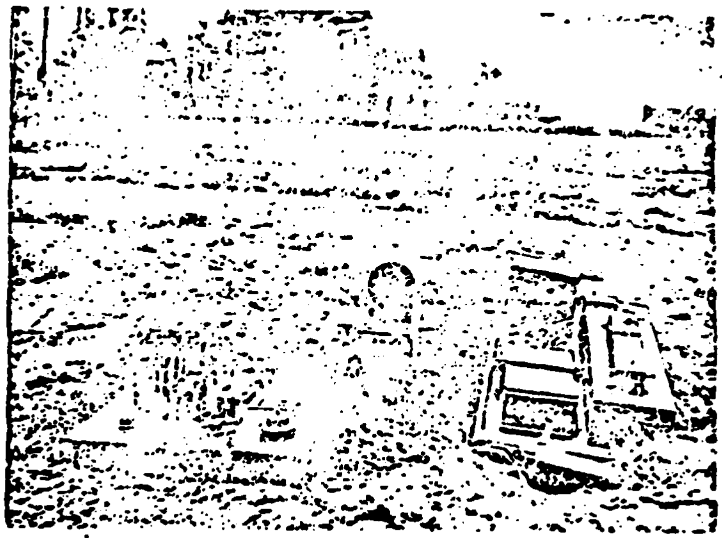

Fig. 3. Instruments for measuring soil ε and σ. Left: high frequency tube oscillator; right: tube voltmeter; center, rear-voltmeter.

A high-frequency alternating voltage from the nonattenuating-oscillation generator was applied via inductive coupling to the wires of the Lecher system and voltage amplitude between the wires measured at the terminal of a tube voltmeter constructed in accordance with the Khising [transliterated (Hiesing?)] scheme (Figs. 2 and 3). A thermo-milliammeter at the initial point of the Lecher system simultaneously measured t e current. A wave meter measured wavelength. The average value was taken from five measurements for β. Measurements were made within the range λ = 110-175 m. We tried as closely as possible to follow the change in ε and σ as a function of the weather, for which we took measurements for several days in a row as well as following sharp changes in the weather (on rainy days or on hot days without precipitation). Figures 4-7 show a number of the curves of electromagnetic attenuation. The measurements made on 10 July were made following several days on which there had been little precipitation (Fig. 4); 11 July - following a very hard rain which fell on the night of 10-11 July (Fig. 5); 17 July - measurements made after 3-4 very hot days without precipitation (Fig. 6); 23 July - measured following a rain falling the night of 22-23 July and into the morning of the 23d (Fig. 7). By comparing the attenuation curves in Figs. 4 and 5 for the 110-112 m waves and in Figs. 6 and 7 for the longer waves, we

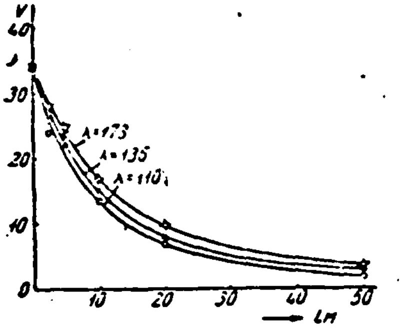

Fig. 4.

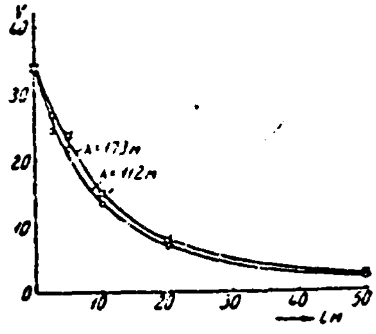

Fig. 5.

Fig. 4. Curves of electromagnetic wave attenuation in Lecher system. Measured 10 July.

Fig. 5. Curves of electromagnetic wave attenuation in Lecher system. Measured 11 July.

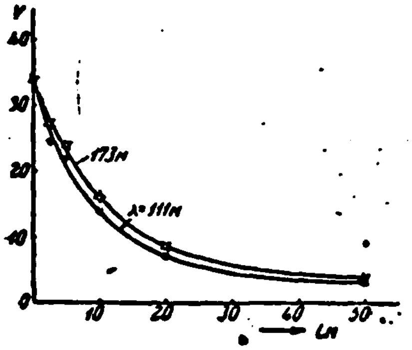

Fig. 6.

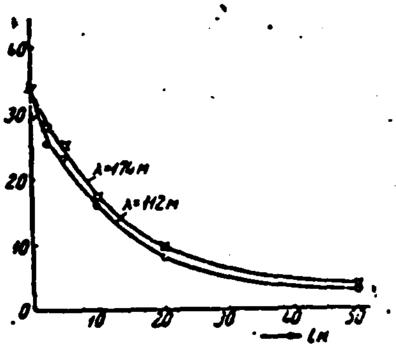

Fig. 7.

Fig. 6. Curves of electromagnetic wave attenuation in Lecher system. Measured 17 July.

Fig. 7. Curves of electromagnetic wave attenuation in Lecher system. Measured 23 July.

can see that the increase in soil moisture does not increase attenuation of the 110-170 m electromagnetic waves. To explain this by simple measurement error would involve some risk, what with the fact that Strutt [6] mentions a similar phenomenon. Table 1 shows our measured values for soil ε and σ. To the information given above on the weather preceding our measurements, we might add the following: 22 June - measurement made after fairly long rainy period; 2 July - after several dry and windy days; 4 July - immediately after short but hard rain. As can be seen from the table, ε varies between 9 and 19 electrostatic units. As was to be expected, the value of ε proved

closely related to soil moisture content: it is substan'ially higher after periods of rain. In calculations for long grounds in coarse-grain sandy soils, we must, of course, take the greatest of the values found for ε, what with the fact that, as was pointed out above, the periods in which this kind of ground will be functioning are by definition periods of stormy weather and, accordingly, rain. Within the range of our measurements, ε is not a function of wave gth. Variations in these values (see Table 1), by virtue of the fact that they exhibit no regularity, must be attributed to the inevitable experimental error. On the other hand, in measurements made on any given day with different wavelengths there is clearly a regularity in variations in the value of (σ): with an increase in wavelength, σ always decreases. The difference in this value observed in a series of measurements made between 22 June and 23 July (Table 1) points to the formation in the soil of compound ion complexes closely associated with changes in weather conditions.

Of some interest is the question of the velocity at which electromagnetic waves propagate in a Lecher system. For this value (from equation 8) we obtain the expression

$$V = c\sqrt{\frac{\varepsilon + \sqrt{\varepsilon^2 + \left(\frac{\sigma}{\varepsilon_0 \omega}\right)^2}}{2}},$$

where c represents the speed of light.

Table 1. Values of soil ε and σ measured at different wavelengths and under different weather conditions in 1934.

Дата измерения (1)	Длина волны в м (2)	$\sigma \cdot 10^{-5}$ сименс/см (3)	ε	Дата измерения (1)	Длина волны в м (2)	$\sigma \cdot 10^{-5}$ сименс/см (3)	ε
22 июня	110	1,94	19,0	10	110	1,81	12,5
2 июля	173	1,36	12,8	11	173	1,88	17,3
2	110	1,40	11,0	11	112	1,47	16,0
4	109	1,65	15,2	14	173	1,68	13,6
4	170	1,55	13,8	14	139	1,71	13,9
9	110	1,66	12,8	14	113	1,85	13,6
9	172	1,59	14,2	17	173	1,34	9.2
9	138	1,63	13,8	17	111	1,49	10,0
10	173	1,35	13,0	23	174	1,50	15,5
10	136	1.68	12,2	23	112	1,61	14,0

KEY: (1) Date measurement; (2) Wavelength in m; (3) Siemens.

For values of ε and σ obtained from measurements on 22 and 17 June V is equal to 0.22 C and 0.27 C respectively.

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